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LCA FOR WASTE

Environmental impact of two aerobic composting technologies using life cycle assessment

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Abstract

Background, aim, and scope Composting is a viable technology to treat the organic fraction of municipal solid waste (OFMSW) because it stabilizes biodegradable organic matter and contributes to reduce the quantity of municipal solid waste to be incinerated or land-filled. However, the composting process generates environmental impacts such as atmospheric emissions and resources consumption that should be studied. This work presents the inventory data and the study of the environmental impact of two real composting plants using different technologies, tunnels (CT) and confined windrows (CCW).

Materials and methods Inventory data of the two composting facilities studied were obtained from field measurements and from plant managers. Next, life cycle assessment (LCA) methodology was used to calculate the environmental impacts. Composting facilities were located in Catalonia (Spain) and were evaluated during 2007. Both studied plants treat source separated organic fraction of municipal solid waste. In both installations the analysis includes environmental impact from fuel, water, and electricity consumption and the main gaseous emissions from the composting process itself (ammonia and volatile organic compounds).

Results and discussion Inventory analysis permitted the calculation of different ratios corresponding to resources consumption or plant performance and process yield with respect to 1 t of OFMSW. Among them, it can be highlighted that in both studied plants total energy consumption necessary to treat the OFMSW and transform it into compost was between 130 and 160 kWh/t OFMSW. Environmental impact was evaluated in terms of global warming potential (around 60 kg CO_2/t OFMSW for both plants), acidification potential (7.13 and 3.69 kg SO_2 eq/t OFMSW for CT and CCW plant respectively), photochemical oxidation potential (0.1 and 3.11 kg C_2H_4 eq/t OFMSW for CT and CCW plant, respectively), eutrophication (1.51 and 0.77 kg PO_4^{3-}/t OFMSW for CT and CCW plant, respectively), human toxicity (around 15 kg 1,4-DB eq/t OFMSW for both plants) and ozone layer depletion (1.66×10^{-5} and 2.77×10^{-5} kg CFC^{-11} eq/t OFMSW for CT and CCW plant, respectively).

Conclusions This work reflects that the life cycle perspective is a useful tool to analyze a composting process since it permits the comparison among different technologies. According to our results total energy consumption required for composting OFMSW is dependent on the technology used (ranging from 130 to 160 kWh/t OFMSW) as water consumption is (from 0.02 to 0.33 m^3 of water/t OFMSW). Gaseous emissions from the composting process represent the main contribution to eutrophication, acidification and photochemical oxidation potentials, while those contributions related to energy consumption are the principal responsible for global warming.

Recommendations and perspectives This work provides the evaluation of environmental impacts of two composting technologies that can be useful for its application to composting plants with similar characteristics. In addition, this study can also be part of future works to compare composting with other OFMSW treatments from a LCA perspective. Likewise, the results can be used for the elaboration of a greenhouse gasses emissions inventory in Catalonia and Spain.

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1 Background

The massive growth of industrial activities, population, and urban planning has lead to an increase in waste generation. There is an international consensus about the importance of an adequate waste management and treatment for human health protection and environmental impacts prevention that has been reflected in the legislation for the protection of the environment (Eriksson et al. 2005). For this reason there has been an evolution of municipal solid waste (MSW) management from a non-selective treatment and direct disposal of MSW in controlled or uncontrolled landfills to the use of treatment technologies including the valorization of the organic fraction (OFMSW) and other materials recycling. Nowadays, the OFMSW treatment involves technologies such as composting or anaerobic digestion that result in the degradation and stabilization of organic matter and mass and volume reduction (Haug 1993; Richard 1992). However, composting is at the moment the most widely used technology for the stabilization of organic wastes due to the complexity and economic investment that anaerobic digestion requires.

Composting allows wastes to be valorized, reducing their size and volume and obtaining a valuable final material (compost) that can be used as fertilizer or soil amendment. Composting is an extended technology for treating household wastes, but it is also applied to residuals coming from industrial activities. The composting process is mainly divided into two phases, named decomposition and curing. Pre-treatment and post-treatment processes are necessary to improve the quality of the compost. Although the objective of composting facilities is to reduce the environmental impact related to organic solid wastes, there are unavoidable environmental impacts and social concerns derived from this activity.

In the last years different studies on mass and energy flows related to composting facilities have been carried out to determine the environmental impacts of this type of treatment systems. A major concern has been the study of gasses emitted during the composting process itself (NH_3, volatile organic compounds (VOCs), N_2O, CH_4, and other compounds) that contribute to global warming, acid rain, human toxicity, and to the promotion of photochemical oxidation reactions in the atmosphere (Komilis et al. 2003, Hellebrand and Kalk 2001; Pagans et al. 2006). Simultaneously, emissions to hydrosphere have been also studied to identify impacts related to eutrophication and soil acidification (U.S. EPA, 2006). Mass and energy balances, as well as economic accounts have also been performed (Fricke et al. 2005, Diggelman and Ham 2003).

Other authors have developed mathematical models to analyze MSW management such as, for example, EASE-WASTE (Kirkeby et al. 2005), ORWARE (Sonesson et al. 1997), and WASTED (Diaz and Warith 2005). These tools include the environmental burdens associated to waste management. Weitz et al. (1999) developed an integrated tool to consider environmental and economic concerns of different waste management strategies.

Life cycle assessment (LCA) has been also proposed to support waste management decisions at different levels as it provides a comprehensive view of the processes and impacts involved (Finnveden et al. 2007). A significant number of publications report LCA use for the comparison of different waste management scenarios to quantify the environmental burdens and benefits of the different proposals (Emery et al. 2007; Finnveden et al., 2005; Güereca et al. 2006; Wilson 2002). Other authors studied MSW management systems from different cities or regions as Ankara (Özeler et al. 2006), Phuket (Liamsanguan and Gheewala 2008), Gipuzkoa (Muñoz et al. 2004), or Corfu (Skordilis, 2004) using LCA. LCA has been also applied to the study of waste treatment plants particularly anaerobic digestion plants (Ishikawa et al. 2006). Finnveden et al. (2005) used this tool to test the waste management hierarchy (which gives preference to recycling over incineration or landfilling) and to determine the situations where this hierarchy is not environmentally valid.

Some methodological aspects have to be considered when LCA is applied to waste management systems such as the definition of system boundaries, the multi-input allocation and open-loop recycling allocation (Finnveden 1999). It is also important to notice that LCA in MSW management systems includes a wide variety of data necessary to perform the required inventory. Although some operations in waste management are independent on the specific characteristics of the waste processed, some others are strongly related to these characteristics (Barton et al. 1996). In many cases data collected in LCA inventory is deduced or directly obtained from bibliographic references or data bases (Güereca et al. 2006; Ménard et al. 2004). This practice may derive in the use of erroneous data when waste management operations are dependent on waste characteristics, which increases results uncertainty. Studies on waste management options have been considered simplifications of reality implying a number of unclear user assumptions (Finnveden et al. 2007). Thus, the existence of real data on real full-scale waste treatment facilities will help to reduce the inherent uncertainty of LCA.

The aim of this study is to determine the environmental impact of two commonly used composting technologies, in-

vessel (tunnel), and confined windrows composting, using LCA. Data necessary to evaluate the environmental impact have been obtained from two full-scale facilities by means of a questionnaire destined to plant managers and on site emission measurements (for ammonia and VOCs). Obtaining real data on gaseous emissions from composting plants to be used in local or national greenhouse gasses inventories is an additional objective. The stages considered in the LCA study were goal and scope definition, inventory analysis, and impact characterization as impact evaluation and interpretation criteria still lack of international consensus (Güereca et al. 2007; Reap et al. 2008).

2 Materials and methods

2.1 Composting plants

The two composting plants, both treating source separated OFMSW, were studied during 2007. Figure 1 shows the general operation flowchart of each plant.

The composting tunnels (CT) facility is located in Girona province (Catalonia, Spain). This plant treats around 6,000 t OFMSW/year using wood chips as bulking agent. The decomposition phase is carried out in closed reactors (tunnels) during 2 weeks under controlled conditions of aeration and watering. The curing phase takes place in forced-aerated windrows during 6–8 weeks. Gaseous emissions coming from the pre-treatment area (trommel screen and mixing) and composting tunnels are treated in a wet scrubber followed by a biofilter. The leachate produced is collected and treated in a nearby municipal wastewater treatment plant. Destination of the compost produced is agriculture and civil works.

The second plant is located in Barcelona province (Catalonia, Spain). This plant uses a composting technology based on confined windrows (CCW) treating around 91 t OFMSW/year using pruning waste as bulking agent. The process consists of a decomposition phase in confined windrows with controlled aeration and watering during 4 weeks followed by 6–8 weeks in a turned windrow (curing phase). Specifically, the waste to be composted is disposed in concrete-made open trapezoidal containers which basis is perforated to provide aeration and collect leachate that is stored in a separated tank. The waste is partially covered with textile linen that prevents water losses and protects from rainfall retaining compost properties. Each container is considered a confined aerated windrow. The studied plant consists of one single container. During the decomposition phase the produced leachate is used to water the material in the confined windrow. The final compost is primarily used in nursering and agriculture.

OFMSW treated in CT plant comes from a street bin collection system whereas the CCW plant treats OFMSW from a door to door collection system.

In general, the CT plant represents a composting plant of medium-to-large capacity, with high investment cost and air cleaning, whereas the CCW plant is a low-cost small scale

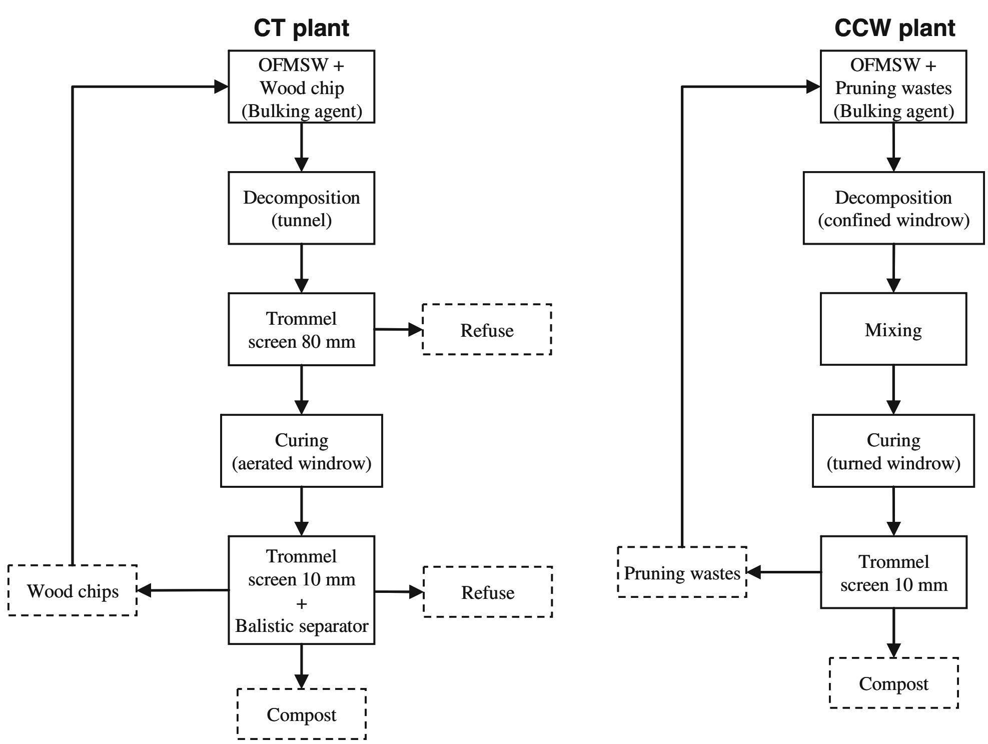

Fig. 1 Flowchart of the studied composting processes. Composting in tunnels (*CT*) and composting in confined windrow (*CCW*)

plant, open to the atmosphere and without complex equipment. Nevertheless, and taking into account that the scale up of the process would simply consist of increasing the number of containers but maintaining the same process conditions (amount of waste in each container, shape, and dimensions of the windrow, aeration rate, bulking agent–OFMSW ratio, etc.), the CCW plant can be considered representative of any plant capacity if this technology is selected.

2.2 LCA methodology

2.2.1 Goal and scope definition

The scope of the present study is to compare two composting technologies from an environmental point of view: tunnels and confined windrows. The functional unit chosen is the treatment of 1 t of source-selected OFMSW. This functional unit will permit the comparison of both studied composting plants regardless its treatment capacity.

2.2.2 System boundaries

LCA was basically performed on the composting plants, excluding transportation of OFMSW, compost, and refuse to its final destinations and wastewater treatment. Fuel, electricity, and water consumption as well as atmospheric emissions were deeply studied. System boundaries and input and output flows considered are represented in Fig. 2.

2.2.3 Inventory analysis

The methodology used for the inventory of the burdens associated to the composting plants was a combination of a questionnaire destined to plant managers and a systematic sampling campaign. Data on amounts of treated OFMSW, refuse, and compost production and electricity and water consumption were obtained by means of this questionnaire.

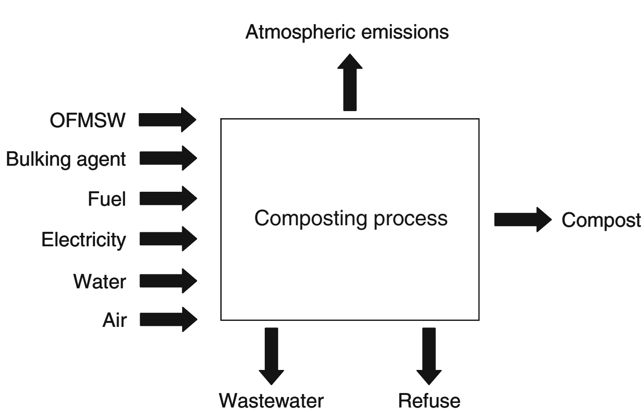

Fig. 2 Input and output flows analyzed in both composting plants

Data on the questionnaire related to process operational conditions (days of treatment, aeration conditions, etc.) were also checked and confirmed in situ. Emissions of ammonia and VOCs were determined in situ or at laboratory as explained bellow.

Gaseous emissions released to the atmosphere came from biofilters and curing windrows surface in CT plant and from the confined windrow and curing windrow surface in CCW plant. For this reason, different sampling points were established in each of these surfaces where exhaust gasses velocity and ammonia and VOCs concentration were simultaneously measured. Ammonia concentration in gaseous emissions was determined in situ using an ammonia sensor ITX T82 (Oakdale, PA, USA) with a measurement range of 0 to 200 ppmv. VOCs concentration was determined by gas chromatography in the laboratory from gaseous samples obtained in the composting plant in 1 L Tedlar bags (Colón et al. 2009). Output gas velocity in composting windrows and biofilters surface was determined by means of a hot wire anemometer (Velocical Plus, mod. 8386, TSI Airflow Instruments, UK), velocity range from 0.01 to 30 m/s, and a Venturi (Veeken et al. 2002). The product of the gasses velocity by the contaminant concentration allowed the calculation of the contaminant mass flow per surface unit (mg contaminant s^{-1} m^{-2}). The product of this value by the surface area results in the contaminant mass flow in each surface area unit. The sum of all the values obtained during a sampling day permits the calculation of the daily amount of contaminant emitted from a plant. These measures were taken in different days during the whole period of study (3 months) to finally obtain the total quantity of contaminant (ammonia and VOCs) emitted to the atmosphere during that period, which can be considered representative for a full-scale composting plant.

Emissions from diesel and electricity consumption in the composting plants were derived from the BUWAL 250 database in Simapro 7.0 (BUWAL, 1998). The electricity model considers the consumption of electricity produced in Spain including production and transport of primary energy sources. The fuel consumption model considers the Heat Diesel B250, from 1 kg of diesel. It includes the emission data of the primary energy sources (Goedkoop 2004).

2.2.4 Impact characterization

Impact categories considered in the analysis were global warming (GWP100), acidification (ACP), photochemical oxidation (PO), eutrophication (EU), human toxicity (HT), and ozone layer depletion (ODP), since these categories have been considered in similar studies (Banar et al. 2009; Blengini 2008; Emery et al. 2007; Eriksson et al. 2005).

3 Results

3.1 Inventory analysis

Data collected in the inventory stage were used to calculate different ratios related to the composting process. These ratios (Table 1) include the efficiency of the composting process with regard to the amount of compost produced (t compost/t OFMSW), the generation of refuse (t refuse produced/t OFMSW), and the efficiency of the pre-treatment step (t refuse produced/t refuse initially present in OFMSW). The refuse produced corresponds to the amount of material separated from the OFMSW in pre- and post-treatment steps, while refuse initially present in OFMSW was obtained from data published by the Catalan Waste Agency based on periodical characterizations of OFMSW during the studied period (Agència de Residus de Catalunya 2007). Finally, ratios related to resources consumption efficiency (kWh/t OFMSW, L diesel/t OFMSW and m^3 water/t OFMSW) were also calculated. Plant managers provide extensive and reliable data on the above-mentioned parameters.

Total energy consumption was calculated assuming that 1 L of diesel produces 10.6 kWh (Queensland EPA 2008). As it can be observed in Table 1, the total consumption of energy in CCW plant is higher than that of the CT plant (161.4 and 133.4 kWh/t OFMSW, respectively) while CT plant has a higher consumption of electricity than CCW plant (95 kWh/t OFMSW and 65.5 kWh/t OFMSW, respectively).

Regarding water consumption, CT plant consumes 16 times more water than CCW plant (0.33 and 0.02 m^3 water/t OFMSW, respectively). Two main reasons can explain this difference. The first one is that watering of the material during the composting process is more intensive in CT plant than in CCW plant. Additionally, in CCW plant leachate is used to water the windrow during the decomposition phase to reduce water consumption. The second reason is a particular characteristic of the studied CT plant regarding its location next to a municipal wastewater treatment plant (MWWTP). This fact allows plant managers to use treated water from the MWWTP in the wet scrubber to treat gaseous emissions (mainly ammonia) to the atmosphere. In this sense, the scrubber system in CT plant works with an open water circuit whereas CCW plant does not have gas emission treatment.

3.2 Impact characterization

Inventory data for each composting plant was classified into different categories for impact characterization following the LCA methodology that are represented in Fig. 3. Emissions from electricity consumption (in white), fuel consumption (in gray), and organic matter degradation (in black; ammonia and VOCs) during composting were used to calculate the different impact potentials. Impact categories analyzed were: global warming, acidification, photochemical oxidation, eutrophication, human toxicity, and ozone layer depletion.

In addition to the values presented in Fig. 3, Table 2 summarizes the contribution percentages of each emission source to the total value of the impact potentials for the two composting plants.

Global warming potential Impacts of electricity, fuel, and process emissions on global warming are shown in Fig. 3a. Results obtained for CT and CCW plants are very similar (63.9 and 63.15 kg CO_2 eq/t OFMSW, respectively). Process contribution to GWP100 was negligible since CO_2 produced during the composting process has not been considered as it comes from a biogenic source (Rabl et al. 2007).

Table 1 Inventory analysis for the two composting technologies, tunnels system (CT) and confined windrow (CCW)

	Units	CT	CCW
Process inputs			
Waste treated	t OFMSW/year	6,082	91
Resources consumed	kWh electricity/t OFMSW	95	65.5
	L Diesel/t OFMSW	3.6	9
	Total energy kWh/t OFMSW	133.4	161.4
	m^3 water/t OFMSW	0.33	0.02
Process outputs			
Atmospheric emissions	kg VOC emitted/t OFMSW (process emissions)	0.205	7.3
	kg NH_3 emitted/t OFMSW (process emissions)	3.9	2
	kg CO_2 emitted/t OFMSW (energy-related emissions)	60.4	60.2
	kg VOC emitted/t OFMSW (energy-related emissions)	0.087	0.176
Final product	t compost/t OFMSW	0.093	0.52
Solid waste generated	t refuse produced/t OFMSW	0.25	–[a]
	t refuse produced/t refuse initially present in OFMSW[b]	2.5	–[a]

Data is related to the treatment of 1 t of OFMSW (functional unit)

[a] Negligible, refuse recycled into the process

[b] Refuse present in OFMSW input determined as established by the Agència de Residus de Catalunya (2007)

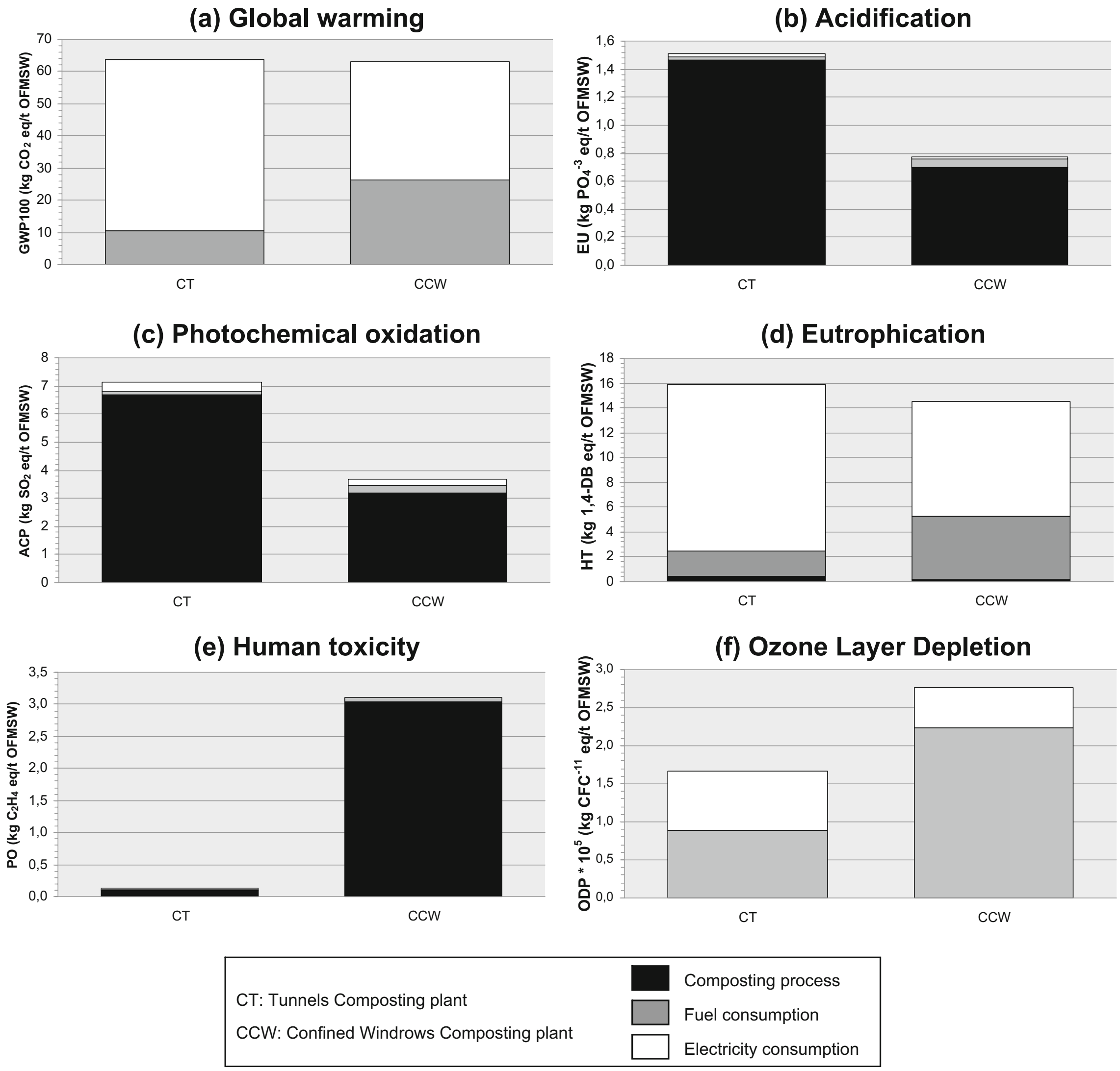

Fig. 3 Environmental impacts comparison in the two composting plants studied (tunnels composting, CT and confined windrows composting, CCW): (**a**) global warming, (**b**) acidification, (**c**) photochemical oxidation, (**d**) eutrophication, (**e**) human toxicity, (**f**) ozone layer depletion. *Black bars* correspond to the contribution of composting process to each category, *gray bars* are related to fuel consumption impacts and *white bars* to electricity consumption

Acidification potential Environmental impact on acidification is shown in Fig. 3b. In both plants the main contribution on acidification is produced by process emissions, particularly ammonia emissions. CT plant acidification potential is higher than that of CCW plant (7.13 and 3.7 kg SO_2 eq/t OFMSW, respectively). Ammonia process emissions in CT plant represents 94% (6.70 kg SO_2 eq/t OFMSW) of the total ACP and 87% (3.2 kg SO_2 eq/t OFMSW) for the CCW plant. In the CT plant emissions from the decomposition phase (tunnel) and the reception zone are treated with a wet scrubber and a biofiltration process (with an ammonia removal yield near 100%, data not shown) while those from the curing phase are directly released to the atmosphere being responsible for the overall ammonia emissions.

Photochemical oxidation Contribution of fuel and electricity consumption and process emissions to photochemical oxidation potential is presented in Fig. 3c. Process emissions (0.09 kg C_2H_4 eq/t OFMSW and 3.03 kg C_2H_4 eq/t OFMSW for CT and CCW plants, respectively) represent the main contribution in PO value in both cases. VOCs emitted during composting process are the main responsible. In case of CT plant VOCs emissions are considerably lower than those from the CCW plant due to gas treatment and the low emission of VOCs during the curing phase.

Table 2 Impact characterization results (impact potentials) for the two composting technologies, tunnels (CT), and confined windrow (CCW) including the contribution of composting process, fuel, and electricity consumption to the total value of the potential (percentage contribution of each item to the total value of the plant in brackets)

Impact potentials	Plant							
	Tunnel composting (CT)				Confined windrows composting (CCW)			
	Process	Fuel	Electricity	Total	Process	Fuel	Electricity	Total
Global warming	0	10.55	53.35	63.90	0	26.37	36.78	63.15
(kg CO_2 eq/t OFMSW)	(0%)	(16.5%)	(83.5%)		(0%)	(41.8)	(58.2)	
Acidification	6.70	0.11	0.32	7.13	3.2	0.27	0.22	3.7
(kg SO_2 eq/t OFMSW)	(94%)	(1.5%)	(4.5%)		(86.7%)	(7.3%)	(6%)	
Photochemical oxidation	0.09	0.03	0.009	0.13	3.03	0.07	0.007	3.11
(kg C_2H_4 eq/t OFMSW)	(69.8%)	(23.2%)	(7%)		(97.6%)	(2.2%)	(0.2%)	
Eutrophication	1.47	0.024	0.017	1.51	0.7	0.06	0.01	0.77
(kg $PO_4{}^{3-}$ eq/t OFMSW)	(97.3)	(1.6%)	(1.1%)		(90.7%)	(7.8%)	(1.5%)	
Human toxicity	0.42	2.04	13.4	15.86	0.2	5.1	9.24	14.54
(kg 1,4-DBeq/t OFMSW)	(2.6%)	(12.9%)	(84.5%)		(1.4%)	(35%)	(63.6%)	
Ozone layer depletion	0	8.9×10^{-6}	7.7×10^{-6}	1.66×10^{-5}	0	2.24×10^{-5}	0.53×10^{-6}	2.77×10^{-5}
(kg CFC^{-11} eq/t OFMSW)	(0%)	(53.8%)	(46.2%)		(0%)	(80.9%)	(19.1%)	

Eutrophication As it has been observed for ACP, ammonia emissions during the composting process are the main contributors to the eutrophication potential (Fig. 3d). Distribution was 97% for the CT plant (1.47 kg PO_4^{3-} eq/t OFMSW) and 91% for the CCW (0.70 kg PO_4^{3-} eq/t OFMSW). Contribution of energy consumption to the eutrophication potential was practically negligible.

Human toxicity Fuel and energy consumption are the main contributors to human toxicity potential (Fig. 3e). In CT plant, electricity consumption caused 84.5% of the total HT potential whereas only 13% was derived from fuel consumption. In relation to CCW, electricity consumption caused 63.6% of this category and 35% was derived from fuel consumption.

Ozone layer depletion ODP is mainly derived from energy consumption. In this study, 1.66×10^{-5} and 2.77×10^{-5} kg CFC^{-11} eq/t OFMSW for CT and CCW plant respectively were calculated (Fig. 3f). Fuel consumption represents the major impact with 54% of contribution in the CT plant and 81% in CCW plant. In this case, since in CCW plant the fuel consumption is higher than in CT plant, ODP is also higher in CCW plant than in CT plant.

4 Discussion

As previously explained, the OFMSW treated in the two composting plants came from different collection systems. Although waste collection is not included within the boundaries of the system, the strong relationship between solid waste generation ratios in Table 1 and the reported waste collection systems should be highlighted. Door to door collection system used in CCW plant is more efficient in terms of OFMSW final quality than street bin collection system used in CT plant (refuse production ratios of 1% and 25%, respectively, see Table 1). This fact has also been stated in other studies (Alvarez et al. 2008) and determines the complexity of the implemented pre and post-treatment operations (see Fig. 1). Complexity of these treatment steps can theoretically affect the energy and water consumption of the entire process. In consequence, some ratios presented in Table 1 are also different.

A large difference between the two plants can be observed in relation to the efficiency of the process in terms of refuse separation from raw OFMSW. This difference is due to the influence of the collection system on the quality of the input OFMSW, but also to the efficiency of pre-treatment and post-treatment operations. A ratio of 2.5 t refuse produced/t refuse initially present in OFMSW has been determined for CT plant while no refuse was produced in CCW plant. Values of this ratio higher than 1 mean that some organic matter is separated as refuse with the consequent loss in the capacity of the plant for compost production.

The ratio t compost/t OFMSW is 5.5-folds higher in CCW plant than in CT plant. Since in general, the more complex a plant is, the less amount of compost is likely to be obtained the presence of impurities is a factor affecting

the results of LCA. Additionally, in CT plant post-treatment operations consist in a trommel screen (10 mm) followed by a ballistic separator while in CCW plant post-treatment operation only consists in a trommel screen (10 mm), which allows some bulking material to remain with the final compost obtained.

On the light of these results it can be stated that the influence of the OFMSW collection system on composting plants impacts requires a more detailed study while, at the same time, it highlights the difficulties in establishing system boundaries in LCA studies about waste treatment and management strategies.

The quality of the compost obtained is an aspect that should be taken into consideration when comparing the impacts of different treatment facilities as few impacts can be derived from a facility producing a low quality product. This can lead to wrong conclusions in terms of environmental impact. Our analysis of the composts obtained show good quality products in both cases.

Electricity is mainly consumed during decomposition and curing phases in CT plant due to forced aeration while in CCW plant forced aeration (and electricity) is only used during decomposition. On the contrary, diesel consumption is higher in CCW plant. This fact can be firstly attributed to the longer distance from decomposition to maturation zones in CCW plant compared to CT plant, which implies larger transportation impacts; and secondly to the fact that mixing and post-treatment processes are performed with diesel machinery in CCW plant while electrical equipment is used in CT plant. However, total energy consumption is higher in CCW plant than in CT plant. According to this, it can be stated that diesel will have a greater contribution to the total energy consumption than electricity. The different use of the energy sources in both plants is also reflected in their contribution to GWP100 values: 83% of the total value of GWP100 is due to electricity consumption in CT plant while this contribution is reduced to 58% in CCW plant, which means 53.35 kg CO_2 eq/t OFMSW and 36.78 kg CO_2 eq/t OFMSW respectively (see Table 2). In both cases the principal compound responsible for the GWP100 value obtained is CO_2 from energy consumed.

Energy consumption is also the major contributor to HT potential for both plants but even though the total energy consumption in CCW is higher than in CT, HT is lower in CCW plant. CCW plant consumes more fuel than CT plant, resulting in a minor impact in the overall HT potential. Therefore, plants consuming fuel should contribute less to HT potential than plants based on electricity. In the case of ODP the situation is inverse being diesel consumption less favorable as a source of energy regarding this impact.

Ammonia emissions come mainly from the composting process in both plants with a negligible contribution of the different energy sources to the final value (see Table 1). This fact is reflected in the contribution percentage of the different emission sources to the values of ACP and EU where ammonia accounts for more than 85% of ACP and EU for both plants (97% in the case of EU for CT plant; see Table 2). Important ammonia emissions during the composting process have also been described by other authors (Hellebrand and Kalk, 2001; Pagans et al. 2006). Exhaust gas treatment in composting processes offers a clear opportunity for reducing the values of ACP and EP, minimizing the environmental burdens of the plant related to these two impact categories. In the case of CT, ammonia present in emissions from the composting tunnels and other parts of the plant is efficiently removed by scrubbing and biofiltration.

The value of PO is mainly due to VOCs emission in both plants especially in CCW plant where this emission represents 97% of PO value. VOCs emitted in diesel consumption in CT plant suppose the 23% of PO. It is evident that PO impact category needs field data on VOCs emission for an accurate evaluation.

Comparing impacts generated by both plants it can be pointed out that the studied configuration of a CT plant has higher impact on EU and ACP potentials due to higher ammonia emission during the process, while the studied configuration of a CCW plant produces a higher impact on PO due to higher VOCs emission during the process and ODP due to a higher fuel consumption. Finally, although energy consumption is the main responsible for global warming and human toxicity and CCW plant presents the highest energy consumption, the different contribution of diesel and electricity to this consumption leads to similar values of GWP100 and HT for both plants.

5 Conclusions

Two composting plants using different composting technologies have been studied during 2007. LCA has been used to calculate environmental impact indicators of each facility. Several conclusions can be obtained from this analysis:

- LCA methodology is an effective tool for analyzing the environmental impact of composting facilities.
- The values of the ratios calculated about plant performance, especially those related to refuse generation, are strongly dependent on the quality of input OFMSW, which at the same time is directly influenced by the collection system used. The importance of the boundaries of the system considered in LCA studies for waste management and treatment operations should be emphasized.
- Gaseous emissions from the composting process represent the main contribution to eutrophication, acidification, and photochemical oxidation potentials in both plants. These

emissions should be carefully determined when using LCA to compare composting technologies. The values of these potentials could be drastically decreased by designing and implementing efficient gaseous emissions treatments in composting facilities.

- According to our results, total energy (electricity and fuel) necessary for OFMSW composting depend on the technology used, ranging from 133 kWh/t OFMSW for CT plant to 160 kWh/t OFMSW for CCW plant. Energy use represents the maximum contribution to global warming, human toxicity, and ozone layer depletion potentials for both plants and the relative values of these potentials depend on the different contribution of electricity and diesel consumption to the total energy used in each plant.
- The different ammonia and VOCs emissions found for the two different composting plants studied and their relative contribution to EU, ACP, and PO values as well as the dependence GWP100, HT, and ODP on the type of energy source used highlight the need of real data. This is strictly necessary to accurately perform LCA studies as the use of general data on the composting process may lead to an increase in results uncertainty.

6 Recommendations and perspectives

This work provides new data on the environmental impact of two different composting technologies. Although LCA has been previously used to compare waste treatment technologies, this is, to the authors' knowledge, the first study where the insights of two composting technologies are systematically studied and compared in terms of environmental impact. In addition, the study of other technologies and facilities will reduce the uncertainty of the inventory data and will improve the quality of the LCA performed. From a technical point of view, it can be stated that the improvement of the process gas treatment can drastically reduce the impact of composting plants. Likewise, the results presented in this paper can contribute to expand the greenhouse gasses emissions inventory in Catalonia.

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